AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **87**, 061112 (2005); doi: 10.1063/1.2009807

View online: http://dx.doi.org/10.1063/1.2009807

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v87/i6

Published by the American Institute of Physics.

Side-chain electro-optic polymer modulator with wide thermal stability ranging from −46 °C to 95 °C for fiber-optic gyroscope applications

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(Received 4 February 2005; accepted 6 July 2005; published online 5 August 2005)

Electro-optic (EO) polymer modulators with a wide range of thermal stability from −46 °C to 95 °C for fiber-optic gyroscope applications are reported. The synthesized EO side-chain polymer used has a glass transient temperature (T_g) of 200 °C and a large EO coefficient of 25.2 pm/V in a real device measurement. Mach–Zehnder (MZ) intensity and optical phase modulators are implemented based on this high-T_g side-chain EO polymer, exhibiting ~3.75 V half-wave voltage with 1.5 cm interaction length and 2.3 cm total length at 1.55 μm wavelength. The optical fiber-to-lens insertion loss is ~7.5 dB in the MZ interferometers and ~6 dB in the straight waveguides. We examine the long-term thermal stability of these devices and demonstrate their ability to meet the strict requirements of various EO device applications, particularly fiber-optic gyroscopes. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2009807]

One of the most important fiber-optic sensors is the fiber-optic gyroscope (FOG), capable of measuring rotation rate. The FOG is a relatively low-cost device with no moving parts and with an improved lifetime compared to conventional mechanical gyroscopes.[1] The efficient interferometric FOG configuration, based on the Sagnac effect, consists of a loop of polarization-maintaining fiber, a multifunctional integrated-optic (IO) circuit, a polarized source, and a detector. Among them, the multifunctional IO circuit on an electro-optic (EO) substrate has been built preferably using lithium niobate ($LiNbO_3$) because of its efficient phase modulation, simplicity, and stability. Since FOGs are subject to extreme temperature changes (−45 °C to 85 °C),[2] the environmental conditions to which integrated optical devices are exposed have become very demanding.

Recently, EO polymer waveguide devices, such as modulators, frequency shifters, and switches for optical communication systems, have been extensively researched.[3–8] However, because of the poor thermal stability of the polymer EO devices associated with the glass transition temperature of the EO chromophore, such an IO circuit has not been implemented using EO polymers despite its many intrinsic advantages, such as high EO coefficient, low cost, and ease of fabrication. Therefore, the temperature stability has been a serious issue that needs to be addressed.

In this letter, low driving voltage polymer modulators based on a low-loss high-T_g side-chain EO polymer material with long-term thermal stability over a wide temperature range are presented. This report demonstrates the ability of EO polymer devices to withstand, and operate at, extreme temperatures without any degradation of performance.

The biggest challenge in EO polymer research is to realize high thermal stability together with other critical properties (i.e., low optical loss and high poling efficiency) in one polymer system under one processing condition. Several approaches of postpolymerization attachment of chromophores have been explored to incorporate chromophores under more friendly conditions; however, desired thermal stability is generally obtained using various crosslinking techniques at the price of low poling efficiency, high optical loss, and complicated poling/curing processes.[9]

After extensive investigation of many types of polymers, we found that polyester is a good candidate because of its mild preparation condition and essentially unlimited possibilities of a monomer structure. We have solved all of the common problems of polyesters, such as low molecular weight, generally low thermal stability, and poor solvent resistance, through judicial design of CLD-attached monomer and co-monomers.[9] The polymer developed, called CX2, and CLD have the basic structures shown in Fig. 1.[10] CX2 is very soluble in chlorinated solvents, such as chloroform, 1,1,2-trichloroethane, yet, is resistant to all common solvents/organic liquids used in the device fabrication. Because of its noncrosslinking nature, the processing is much less complicated compared to crosslinking polymers. Major properties of the EO polymer, such as optical loss

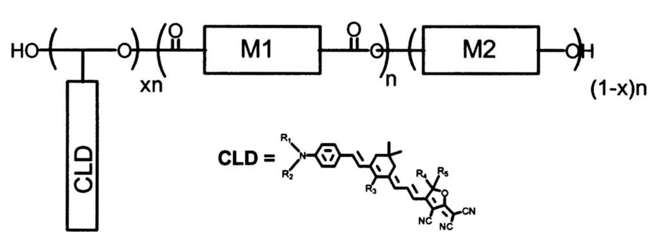

FIG. 1. The basic structure of CX2. CLD is a chromophore with the same π-conjugate system as that of CLD1, M1 is a diacid comonomer, and M2 is a diol comonomer. (An example of the polymer synthetic scheme and structures for M1 and M2 can be found in Ref. 10.)

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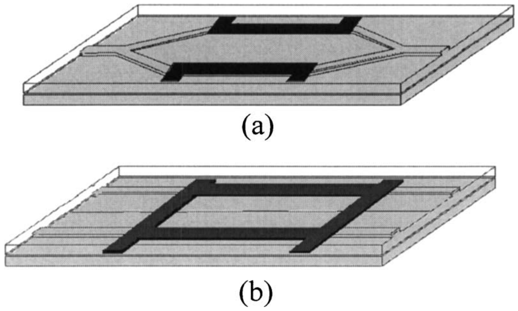

FIG. 2. Schematic diagram of the fabricated EO modulators.

(1.3 dB/cm @ 1.55 μm), thermal stability (long term at temperatures >85 °C), and decent EO activity,[9] have been obtained simultaneously under one processing condition. The high thermal stability of CX2 arises from three design features: (1) The extreme reduction of flexible structural units, such as aliphatic hydrocarbon flexible chains, in the chromophore, (2) a large amount of rigid aromatic monomers, and (3) the incorporation of highly polar structural units, such as imides, in monomer M1 of Fig. 1 to enhance polymer chain interaction. Its excellent processibility has been utilized in the demonstration of vertical transitions between silica and electro-optic planar waveguides fabricated using grayscale lithography with low transition loss.[11]

Figure 2 depicts schematic diagrams of the fabricated devices for the test. Chromium- and gold-coated silicon substrates were used, and a passive polymer (UFC-170A) was spun and ultraviolet (UV)-cured for the lower cladding layer. The EO core layer was spin coated and the ridge waveguide pattern was formed using standard photolithography. The same UV curable polymer (UFC-170A) was used for the upper cladding. The fabricated modulator has ~7.5 μm total thickness, consisting of a 2.5 μm thick core and cladding layers. By applying a poling voltage of 350 V at 190 °C for 5–15 min, the device poling was performed. The Mach–Zehnder (MZ) modulators have an interaction length of 1.5 cm and a total device length of 2.3 cm.

Figure 3 shows a block diagram of the thermal stability test, which consists of a cooling/heating chamber filled with dry nitrogen gas, a phase modulator placed within a fiber optic MZ interferometer formed using 1×2 fiber couplers, a polarization controller, and a signal source/detector. The phase modulator pigtailed with fibers was mounted on a stage where a temperature controller was used to adjust the temperature of the stage as shown in Fig. 4. The insertion loss and half-wave voltage of the phase modulator were monitored as a function of temperature for the comparisons. A thermoelectric cooler in combination with dry ice can

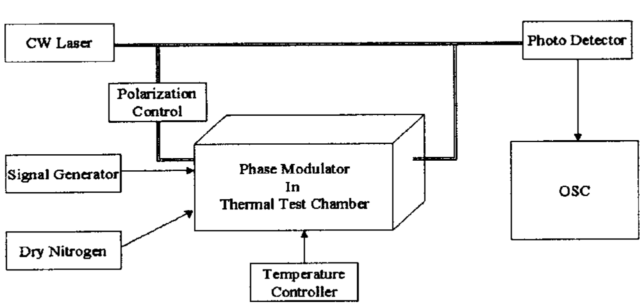

FIG. 3. Block diagram of the experimental setup.

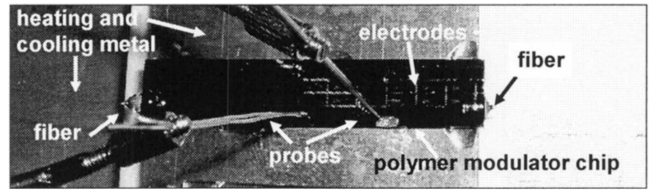

FIG. 4. Fiber-pigtailed device for temperature stability test.

achieve temperatures varying from −46 °C to +60 °C. To minimize any condensation on the phase modulator surface, the chamber was filled with nitrogen gas during the low temperature test.

In order to study the long-term thermal stability of the synthesized side-chain EO chromophore alignment, the phase modulators with 3.5 cm interaction length were constantly heated at 95 °C on a thermally controlled hot plate in air for over one month. The hot plate was covered with a lab-made glass box to maintain temperature uniformity over the surface. The device test was performed in two ways: (1) The modulators were kept at 95 °C and immediately tested, (2) they were first cooled down to the room temperature and then tested. All of the experiments were performed at 1.55 μm wavelength under transverse magnetic mode polarization.

The measured V_π of the MZ device was 7.5 V at 1.55 μm as shown in Fig. 5. Note, for simplicity, a single-arm electrode was used; the V_π for a push-pull device would be 3.75 V, corresponding to an r_{33} coefficient of 25.2 pm/V, which is comparable to that obtained in our earlier work.[9] The extinction ratio of the modulation curve was typically larger than 20 dB. The total fiber-to-lens insertion loss was ~7.5 dB in a MZ interferometer and ~6 dB in a straight waveguide. The optical propagation loss of the synthesized EO material was measured to be 1.3–1.4 dB/cm in a slab waveguide as shown in Fig. 6, while the loss of a rib waveguide was ~1.7 dB/cm at 1.55 μm wavelength.

Figure 7 shows the thermal stability of the half-wave voltage of the fabricated phase modulator as a function of temperature ranging from −46 °C to 60 °C. The experimental results reveal that through the entire temperature range, the V_π of the side-chain EO phase modulator was kept near the initial value that it exhibited at room temperature. The V_π curve has a slight fluctuation of ~1 V which we have attributed to the optical polarization change in the standard (non-polarization maintaining) single-mode optical fibers used in our setup. Therefore, we strongly believe that the V_π was not a function of the examined temperatures. The optical fiber-

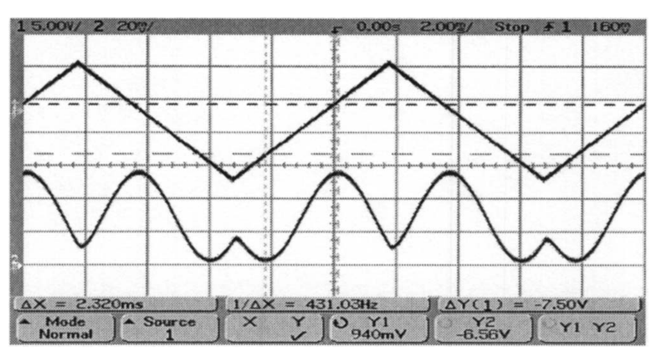

FIG. 5. Low-frequency transfer function measurements at 1.55 μm in single-arm driving operation.

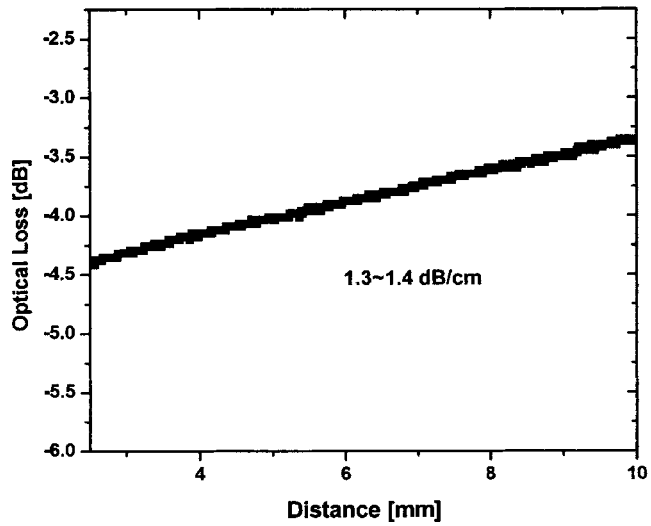

FIG. 6. Optical loss of EO chromophore in a slab waveguide at 1.55 μm by the immersion technique.

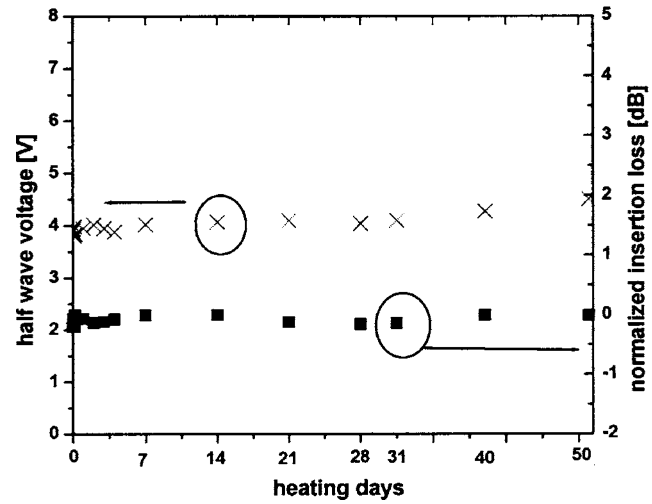

FIG. 8. The thermal stability at 95 °C of EO phase modulator fabricated from the side-chain EO chromophore.

to-fiber insertion loss varied due to the unstable UV-cured epoxy at the input/output port, which was very sensitive to the environmental temperature change. Using an UV-cured epoxy (OP-52, Dymax, USA) (Ref. 12) for the fiber-to-waveguide pigtail, the fiber-to-fiber insertion loss underwent a variation of ~5 dB over the measured temperature range. However, we believe that this optical insertion loss variation can be eliminated if different epoxies or improved fiber pigtail methods are employed.

Figure 8 plots the long-term thermal stability of the phase modulator as a function of heating time, performed at 95 °C in an air atmosphere. As expected, the V_π and the optical insertion loss kept constant after heating at 95 °C in air for 50 days, suggesting that the fabricated optical modulators have excellent thermal stability in high-temperature environments. Accordingly, it was confirmed that the EO half-wave voltage of the side-chain EO polymer modulator was not degraded as a result of heating. This demonstrates that the side-chain polymer modulator can survive and operate at high temperatures with good long-term thermal stability.

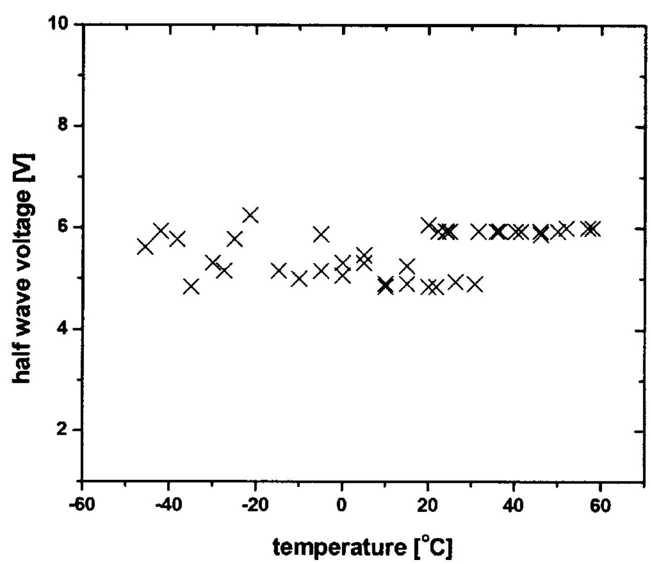

FIG. 7. Thermal stability in half-wave voltage and insertion loss versus cooling/heating temperature. The phase modulator was fiber-connected and mounted on cooling/heating metal inside a nitrogen box filled with dry ice for lower-temperature test.

In summary, we have examined a side-chain EO polymer with a high T_g of more than 200 °C, and used this material to fabricate MZ and phase modulators with excellent long-term thermal characteristics. Our test results confirm that the fabricated EO polymer modulators can meet the strict thermal requirements of fiber-optic gyroscope applications, as well as the other EO polymer applications.

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